

**WHAT IS CLAIMED IS:**

1        1. Apparatus for converting power from an input source for delivery to a load  
2 comprising:

3              a transformer;  
4              a primary switch connected to drive the transformer;  
5              output circuitry connected to the transformer for delivering an output voltage to the  
6 load;

7              a switch controller adapted to operate the primary switches in a series of converter  
8 operating cycles; and

9              modulation control circuitry adapted to modulate the ON-resistance of the primary  
10 switch.

1        2. The apparatus of claim 1 wherein the modulation control circuitry further  
2 comprises an input connected to sense the output voltage and modulates the ON-resistance to  
3 control the output voltage.

1        3. The apparatus of claim 1 wherein the modulation control circuitry further  
2 comprises an input connected to sense the output voltage and modulates the ON-resistance to  
3 limit an output current.

1        4. The apparatus of claim 1 wherein the modulation control circuitry further  
2 comprises an input connected to sense a load current and modulates the ON-resistance to  
3 provide a controlled output current during start-up of the apparatus.

1        5. The apparatus of claim 4 wherein the input is adapted to sense leakage flux in  
2 the transformer.

1        6. The apparatus of claim 1 wherein the modulation control circuitry varies a  
2 voltage used for driving a gate control input of the primary switch.

1        7. The apparatus of claim 6 wherein the voltage is a supply voltage of a gate  
2 drive circuit.

1        8. The apparatus of 1 further comprising:  
2              a resonant circuit including the transformer having a Q less than 13 and having a  
3 characteristic resonant frequency and period;

4              wherein the primary switch comprises two or more primary switches connected to  
5 drive the resonant circuit;

6           wherein the output voltage is rectified;  
7           wherein the load may vary over a normal operating range; and  
8           wherein each converter operating cycle is characterized by two power transfer  
9       intervals of essentially equal duration each interval having a duration less than the  
10      characteristic resonant period, during which one or more of the primary switches are ON and  
11      power is transferred from the input to the output via the transformer; and  
12           comprising a conversion efficiency from the source to the load having a peak greater  
13      than 90% within the normal operating range.

1           9.       The apparatus of claim 1 further comprising:

2           a resonant circuit including the transformer and having a characteristic resonant  
3      frequency and period;

4           wherein the primary switch comprises two or more primary switches connected to  
5      drive the resonant circuit;

6           wherein the output voltage is rectified;

7           wherein the load may vary over a normal operating range; and

8           wherein each converter operating cycle is characterized by

9           (a) two power transfer intervals of essentially equal duration, during which one or  
10      more of the primary switches are ON and power is transferred from the input to the output  
11      via the transformer; and

12           (b) two energy-recycling intervals each having an essentially constant duration over  
13      the normal operating range during which the primary switches are OFF;

14           wherein the switch controller is adapted to turn the primary switches OFF essentially  
15      at times when the current in a secondary winding returns to zero; and

16           magnetizing current is used to charge and discharge capacitances during the energy-  
17      recycling intervals.

1           10.      The apparatus of claim 1 further comprising:

2           a resonant circuit including the transformer and having a characteristic resonant  
3      frequency and period;

4           wherein the primary switch comprises two or more primary switches connected to  
5      drive the resonant circuit;

6           wherein the output voltage is rectified;

7 wherein the load may vary over a normal operating range; and

8 wherein each converter operating cycle is characterized by

9 (a) first and second power transfer intervals during which one or more of the primary  
10 switches are ON, power is transferred from the source to the load via the transformer, and  
11 voltages and currents in the converter rise and fall at the characteristic resonant frequency;  
12 the first and second power transfer intervals being of substantially equal duration over the  
13 normal operating range; and

14 (b) two energy-recycling intervals during which the primary switches are OFF; and

15 (c) a period having an essentially constant duration over the normal operating range;

16 and

17 an essentially constant voltage gain  $K = V_{out} / V_{in}$  at a load current for the power  
18 conversion, where  $V_{in}$  is the input source voltage and  $V_{out}$  is the rectified output voltage;  
19 and

20 wherein magnetizing current is used to charge and discharge capacitances during the  
21 energy-recycling intervals.

1 11. A method for converting power from an input source for delivery to a load  
2 comprising:

3 providing a transformer;

4 providing a primary switch to drive the transformer;

5 providing output circuitry connected to the transformer for delivering an output  
6 voltage to the load;

7 providing a switch controller adapted to operate the primary switch in a series of  
8 converter operating cycles;

9 providing modulation control circuitry adapted to modulate the ON-resistance of the  
10 primary switch.

1 12. The method of claim 11 further comprising

2 providing the modulation control circuitry with an input connected to sense the output  
3 voltage; and

4 further adapting the modulation control circuitry to modulate the ON-resistance to  
5 control the output voltage.

1 13. The method of claim 11 further comprising

2 providing the modulation control circuitry with an input connected to sense the output  
3 voltage; and

4 further adapting the modulation control circuitry to modulate the ON-resistance to  
5 limit an output current.

1 14. The method of claim 11 further comprising  
2 providing the modulation control circuitry with an input connected to sense an output  
3 current; and

4 further adapting the modulation control circuitry to modulate the ON-resistance to  
5 provide a controlled output current during start-up of the apparatus.

1 15. The method of claim 14 wherein the input is adapted to sense leakage flux in  
2 the transformer.

1 16. The method of claim 11 further comprising adapting the modulation control  
2 circuitry to vary a voltage used for driving a gate control input of the primary switch.

1 17. The method of claim 16 further comprising adapting the modulation control  
2 circuitry to vary a supply voltage of a gate drive circuit.

1 18. The method of claim 11 further comprising:  
2 forming a resonant circuit including the transformer having a Q less than 13 and  
3 having a characteristic resonant frequency and period;

4 rectifying the output voltage;  
5 wherein the load may vary over a normal operating range;  
6 wherein the primary switch comprises two or more primary switches connected to  
7 drive the resonant circuit;

8 wherein each converter operating cycle is characterized by two power transfer  
9 intervals of essentially equal duration each interval having a duration less than the  
10 characteristic resonant period, during which one or more of the primary switches are ON and  
11 power is transferred from the input to the output via the transformer; and

12 providing a conversion efficiency from the source to the load having a peak greater  
13 than 90% within the normal operating range.

1 19. The method of claim 11 further comprising:  
2 forming a resonant circuit including the transformer and having a characteristic  
3 resonant frequency and period;

4 providing output circuitry connected to the transformer for delivering a rectified  
5 output voltage to the load;

6 rectifying the output voltage;

7 wherein the load may vary over a normal operating range;

8 wherein the primary switch comprises two or more primary switches connected to  
9 drive the resonant circuit;

10 wherein each converter operating cycle is characterized by

11 (a) two power transfer intervals of essentially equal duration, during which one or  
12 more of the primary switches are ON and power is transferred from the input to the output  
13 via the transformer; and

14 (b) two energy-recycling intervals each having an essentially constant duration over  
15 the normal operating range during which the primary switches are OFF; and

16 using the switch controller to turn the primary switches OFF essentially at times when  
17 the current in a secondary winding returns to zero; and

18 using magnetizing current to charge and discharge capacitances during the energy-  
19 recycling intervals.

20. The method of claim 11 for use in a converter where the primary switch  
comprises two or more primary switches connected to drive a resonant circuit including the  
transformer and having a characteristic resonant frequency and period, where the output  
voltage is rectified, and where the load may vary over a normal operating range, the method  
further comprising:

operating the primary switches in a series of converter operating cycles, each  
converter operating cycle characterized by:

(a) first and second power transfer intervals during which one or more of the primary  
switches are ON, power is transferred from the input source to the load via the transformer,  
and voltages and currents in the converter rise and fall at the characteristic resonant  
frequency of the resonant circuit; the first and second power transfer intervals being of  
substantially equal duration; and

(b) two energy-recycling intervals during which the primary switches are OFF;  
wherein the switch controller turns the primary switches OFF at times essentially  
when the current in a secondary winding returns to zero; and

16       wherein currents in the converter are used to charge and discharge capacitances in the  
17      converter during the energy-recycling intervals; and

18           providing an essentially constant voltage gain  $K = V_{out} / V_{in}$  at a load current for the  
19      power conversion, where  $V_{in}$  is the input source voltage and  $V_{out}$  is the rectified output  
20      voltage across the load.

1           21.     The method of claim 11 for use in a converter where the primary switch  
2      comprises two or more primary switches connected to drive a resonant circuit including a  
3      transformer and having a characteristic resonant frequency and period, where the output  
4      voltage is rectified, and where the load may vary over a normal operating range, the method  
5      further comprising:

6           operating the primary switches in a series of converter operating cycles, each  
7      converter operating cycle being characterized by:

8           (a) first and second power transfer intervals during which one or more of the primary  
9      switches are ON, power is transferred from the source to the load via the transformer, and  
10     voltages and currents in the converter rise and fall at the characteristic resonant frequency of  
11     the resonant circuit; the first and second power transfer intervals being of substantially equal  
12     duration over the normal operating range; and

13           (b) two energy-recycling intervals during which the primary switches are OFF; and  
14           (c) a period having an essentially constant duration over the normal operating range;

15      and

16           using magnetizing current to charge and discharge capacitances during the energy-  
17      recycling intervals.